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Sell et al.

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(54) **MARKERS, PHANTOMS AND ASSOCIATED METHODS FOR CALIBRATING IMAGING SYSTEMS**

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(57) **ABSTRACT**

Embodiments of the present invention provide markers, phantoms, and associated methods of calibration which are suitable for use in both magnetic resonance imaging and radiographic imaging systems. A marker includes a first marker component having a first hydrogen proton density and a first mass density; and a second marker component
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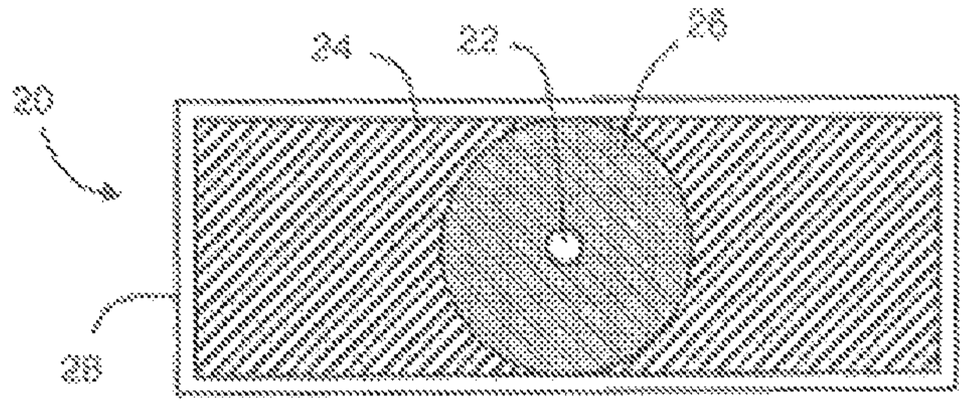

having a second hydrogen proton density different than the first hydrogen proton density, and a second mass density different than the first mass density. The first marker component and the second marker component are non-magnetic.

17 Claims, 5 Drawing Sheets

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G01R 33/58	(2006.01)
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A61B 90/00	(2016.01)

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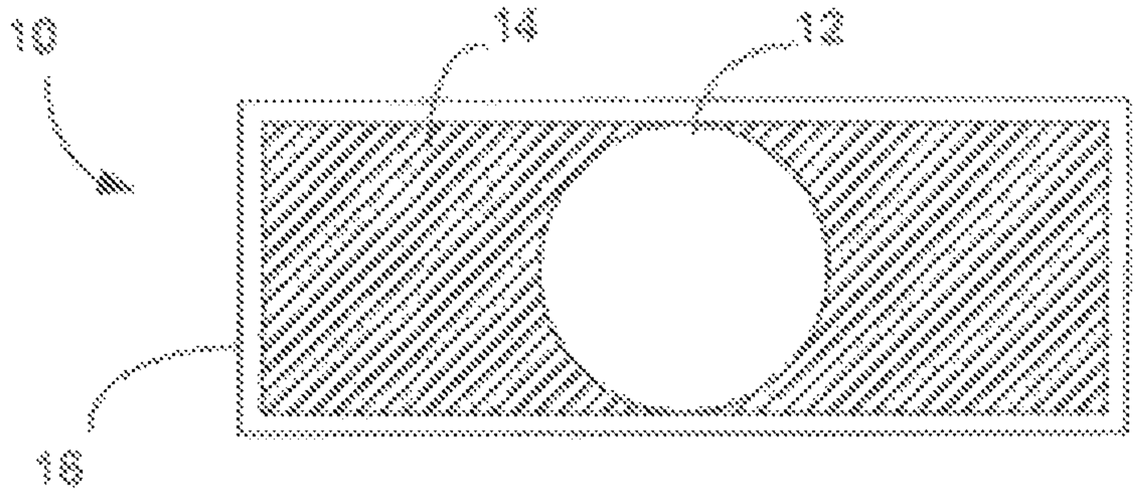

Fig. 1

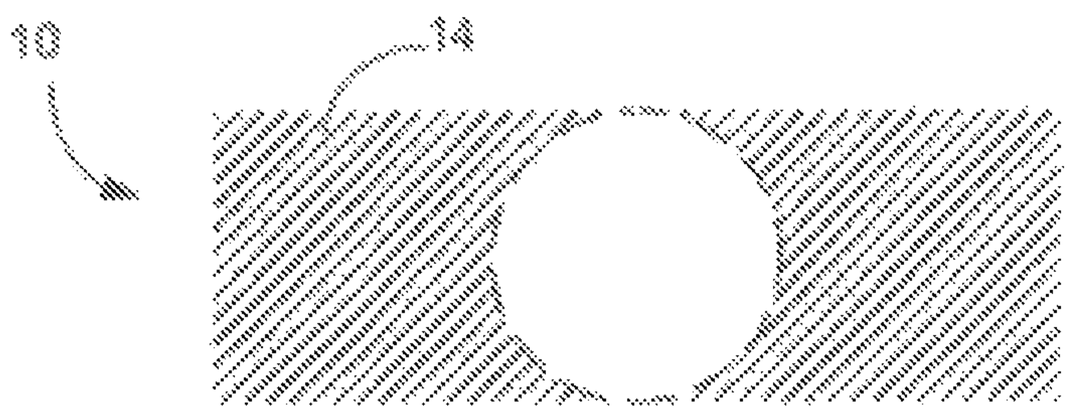

Fig. 2a

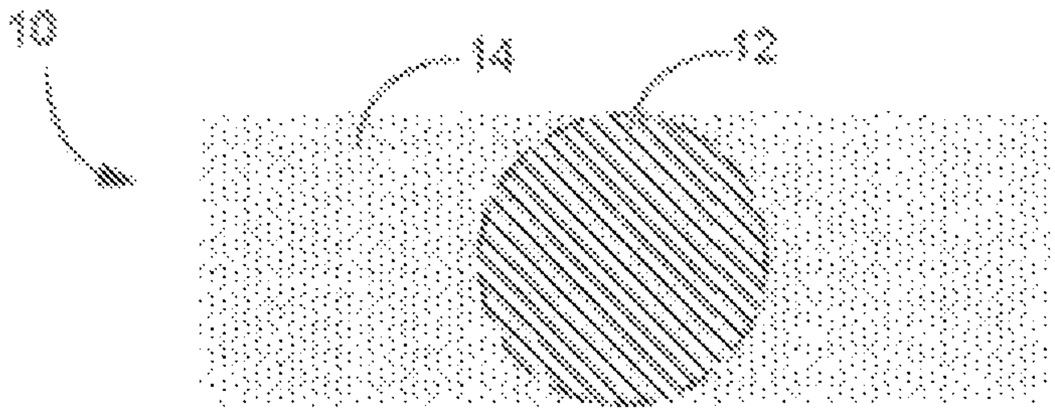

Fig. 2b

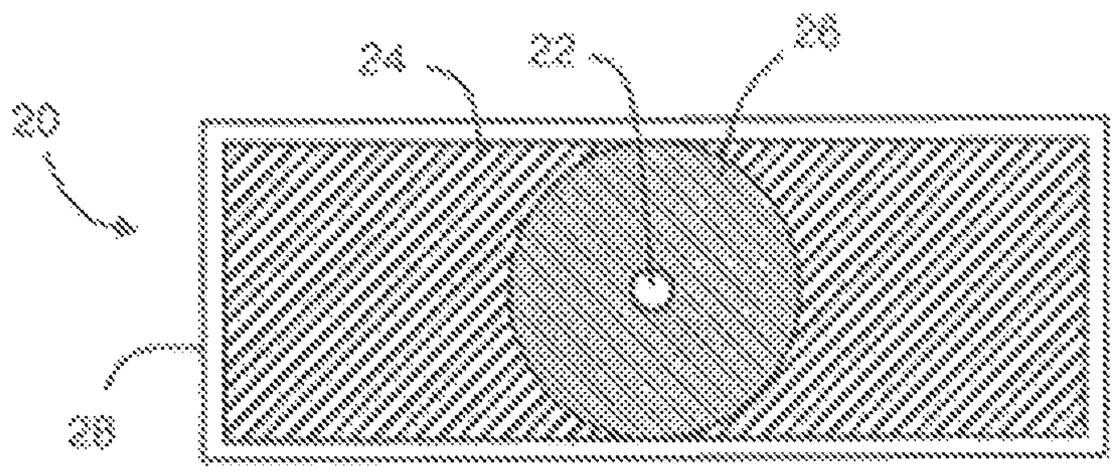

Fig. 3

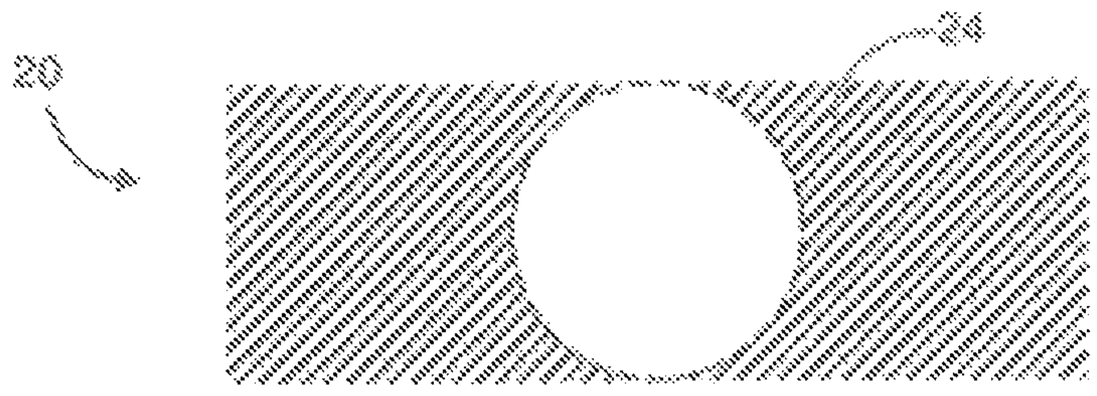

Fig. 4a

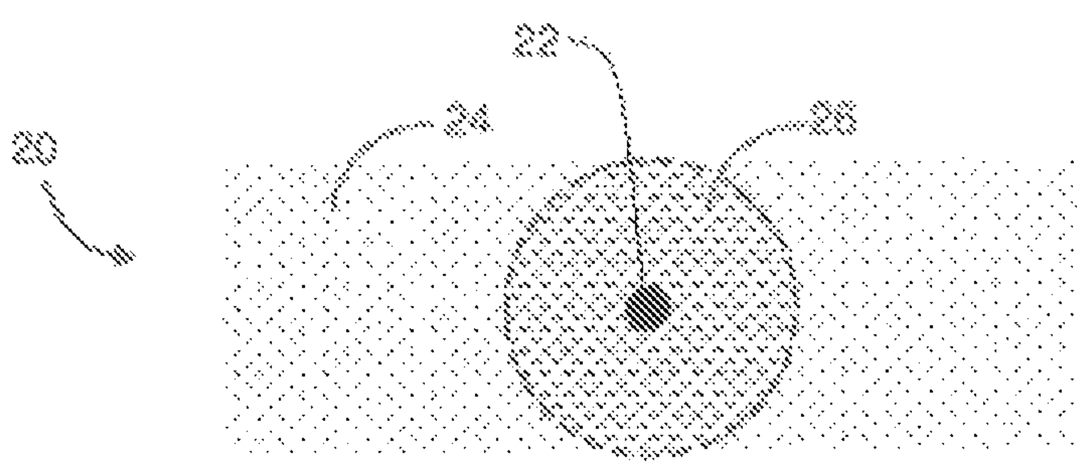

Fig. 4b

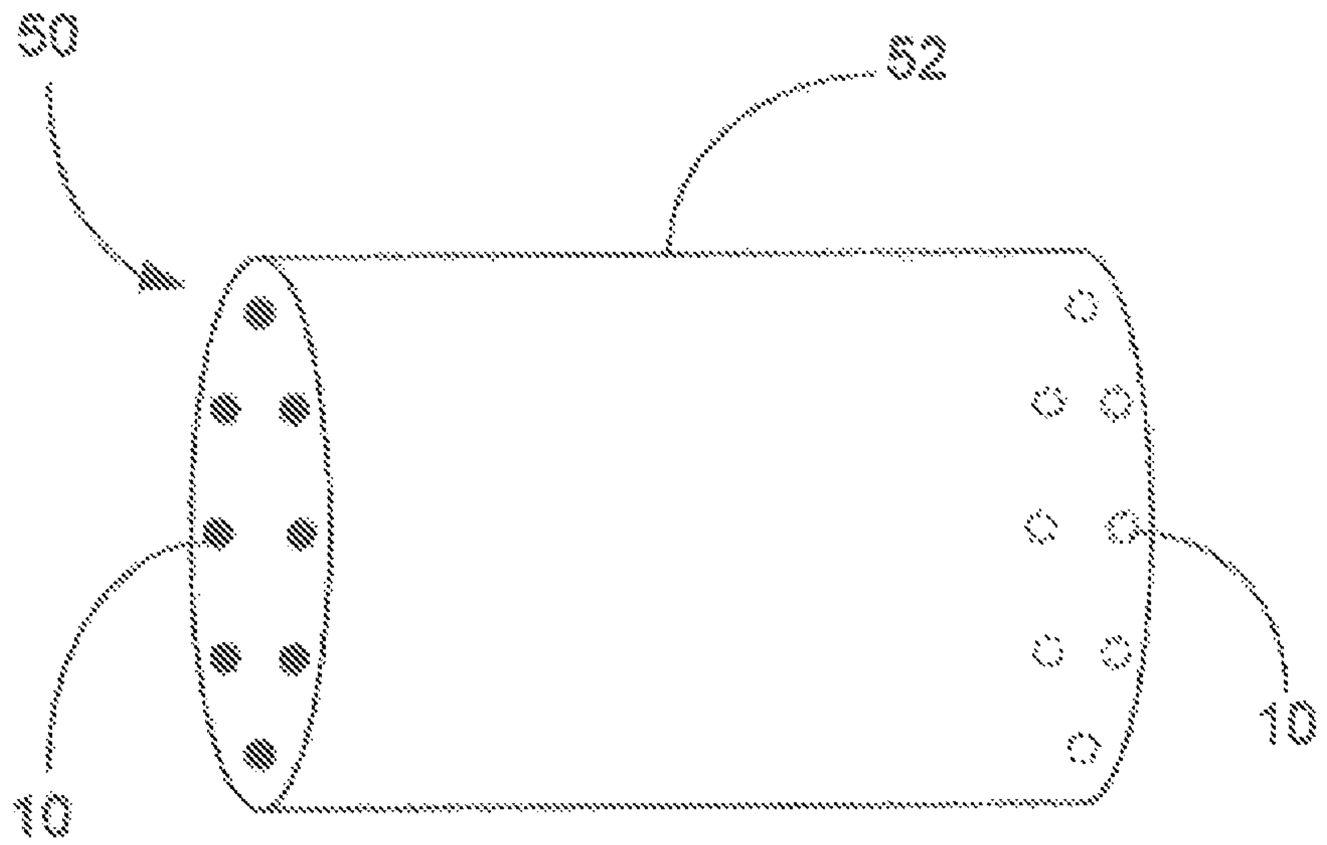

Fig. 5a

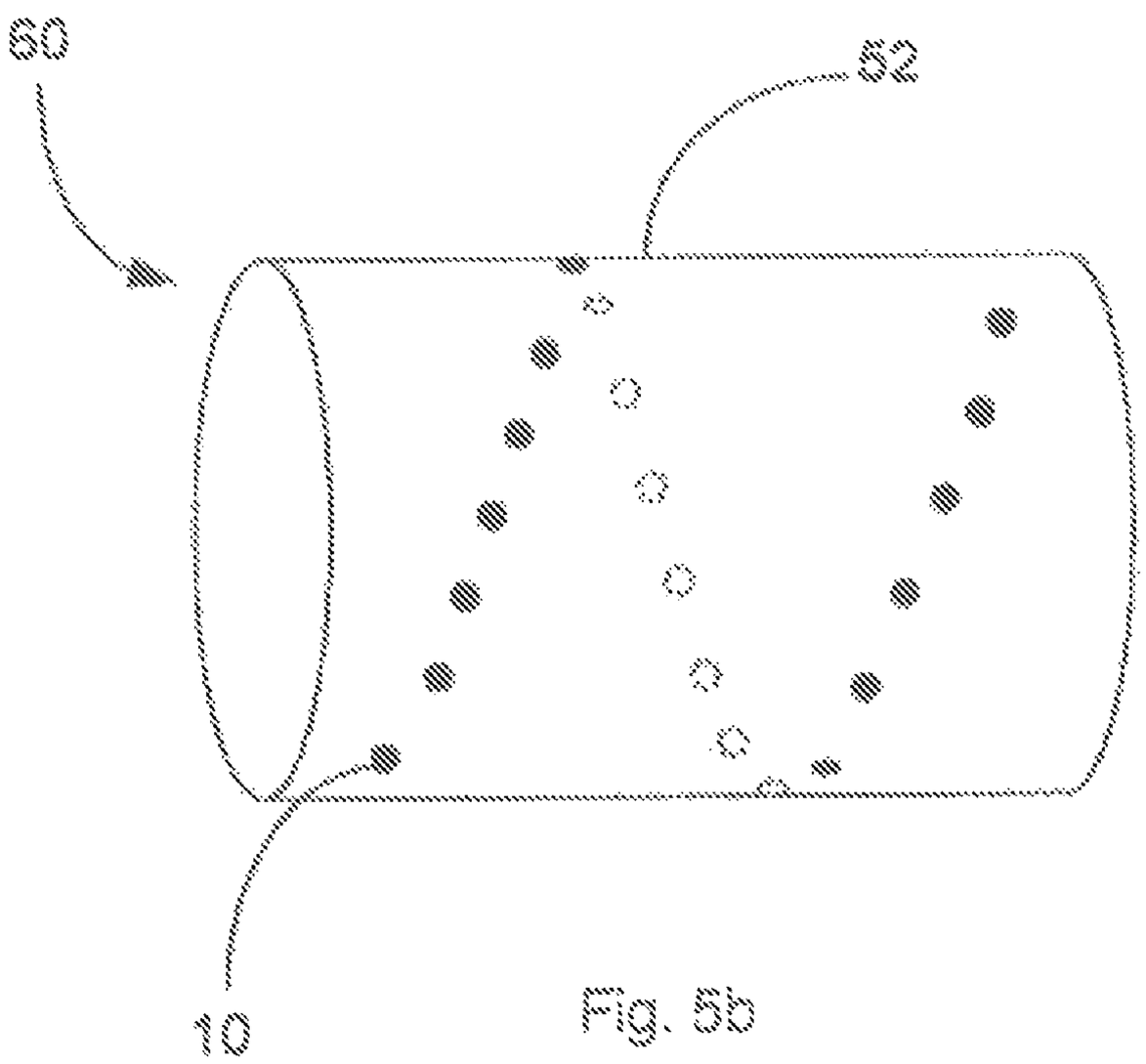

Fig. 5b

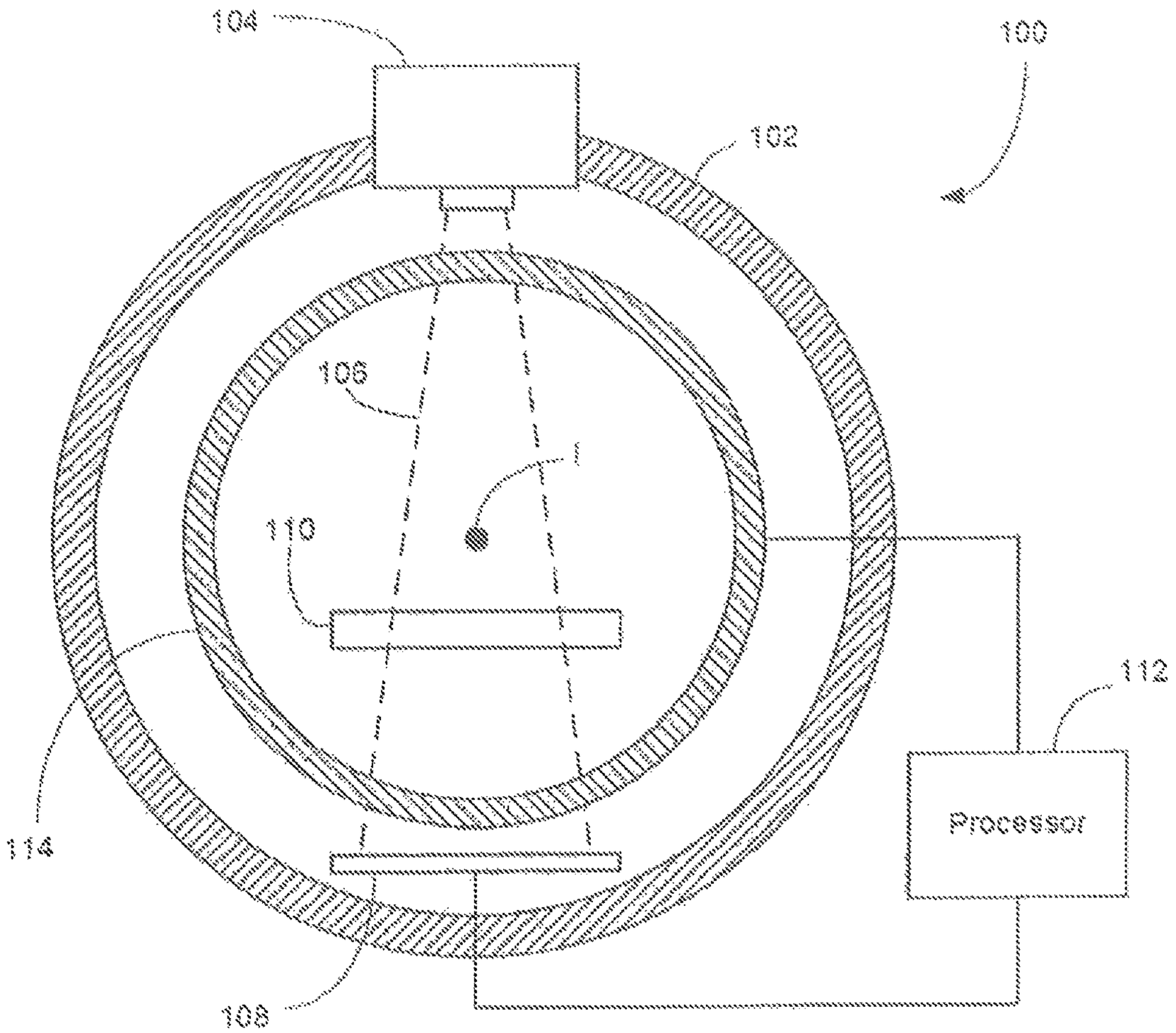

Fig. 6

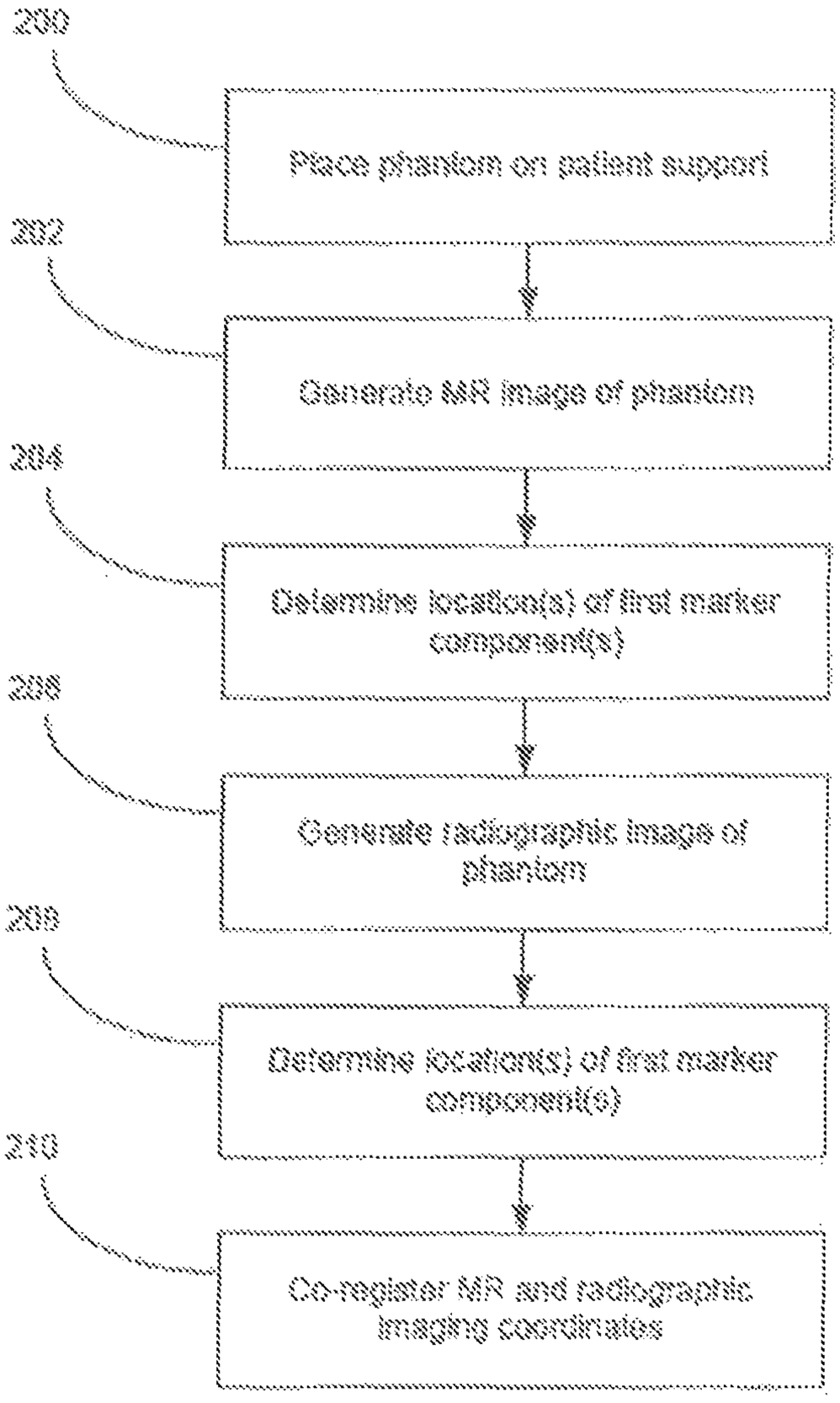
200
Place phantom on patient support
202
Generate MR image of phantom
204
Determine location(s) of first marker component(s)
208
Generate radiographic image of phantom
209
Determine location(s) of first marker component(s)
210
Co-register MR and radiographic imaging coordinates

Fig. 7

MARKERS, PHANTOMS AND ASSOCIATED METHODS FOR CALIBRATING IMAGING SYSTEMS

CROSS-REFERENCE TO RELATED PATENT APPLICATIONS

This application is a National Stage Entry of International Application No. PCT/EP2014/056272, filed Mar. 28, 2014, which claims priority from Great Britain Application No. 1318959.2, filed Oct. 28, 2013, and Great Britain Application No. 1305751.8, filed Mar. 28, 2013. The entire contents of the above-referenced applications are expressly incorporated herein by reference.

TECHNICAL FIELD

The present invention relates to medical imaging, and particularly to markers, phantoms, and associated methods of calibrating an imaging system which may be integrated with a radiotherapy system.

BACKGROUND

Recent developments in the field of radiotherapy have focussed on integrating an imaging system with the therapeutic system. The goal is to provide real-time feedback on the location of an anatomical feature within the patient (e.g. a tumour) such that a therapeutic radiation beam can be more accurately controlled to target that feature.

One suggested approach is to combine a linear accelerator-based therapeutic system with a magnetic resonance imaging (MRI) system within a single apparatus, known as an MRI-Linac. Such apparatus is described in a number of earlier applications by the present Applicant, including U.S. patent application Ser. No. 12/704,944 (publication no 2011/0201918) and PCT publication no 2011/127947. In the system described in each of these earlier applications, the magnetic coils of the MRI system are split, leaving a gap through which a therapeutic radiation beam can be delivered to the patient. In this way, the patient can be imaged and treated substantially simultaneously while lying in the same position.

If the MRI system is to provide reliable information to the therapeutic system, it is important that the two systems are accurately calibrated; that is, the coordinate system of the MRI system must be registered to that of the treatment beam so that measurements in the MRI system can be translated into instructions in the therapy system.

Phantoms are known devices which are scanned or imaged to evaluate and tune the performance of various medical imaging devices. A paper by Rhode et al ("Registration and Tracking to Integrate X-Ray and MR Images in an XMR Facility", IEEE Transactions on Medical Imaging, Vol. 22, pages 1369-1378) describes a method of registering x-ray and MR images in which a phantom is first imaged in an x-ray system before being translated a distance and imaged by an MRI system. The distance between the two systems is measured to enable the two coordinate systems to be co-registered. When in the x-ray system, ball bearings are used as markers within the phantom; when in the MRI system, the ball bearings are replaced by MR imaging markers to avoid problems arising from interactions with the intense magnetic field.

This system has several drawbacks. The replacement of the ball bearings with MR imaging markers introduces a potential source of error if the two markers are not exactly co-located within the phantom. In addition, the translation of the phantom between the two devices introduces a further source of error.

SUMMARY OF INVENTION

According to a first aspect of the present invention, there is provided a marker for use in calibration of a medical imaging system, comprising: a first component having a first hydrogen proton density and a first mass density; and a second component having a second hydrogen proton density different than the first hydrogen proton density, and a second mass density different than the first mass density, wherein the first and second components are non-magnetic.

In further aspects of the invention, phantoms and methods of calibrating imaging systems are provided.

BRIEF DESCRIPTION OF THE DRAWINGS

For a better understanding of the present invention, and to show more clearly how it may be carried into effect, reference will now be made, by way of example, to the following drawings, in which:

FIG. **1** shows a marker according to embodiments of the present invention;

FIG. **2***a* is a schematic illustration of an MR image of the marker of FIG. **1**;

FIG. **2***b* is a schematic illustration of a radiographic image of the marker of FIG. **1**;

FIG. **3** shows a marker according to embodiments of the present invention;

FIG. **4***a* is a schematic illustration of an MR image of the marker of FIG. **3**;

FIG. **4***b* is a schematic illustration of a radiographic image of the marker of FIG. **3**;

FIG. **5***a* shows a phantom according to embodiments of the present invention;

FIG. **5***b* shows a phantom according to further embodiments of the present invention;

FIG. **6** shows a combined MRI radiotherapy system; and

FIG. **7** is a flowchart of a method according to embodiments of the present invention.

DETAILED DESCRIPTION

FIG. **1** shows a cross section of a marker **10** according to embodiments of the present invention. As will be explained below, the marker **10** is suitable for use in a variety of medical imaging systems using different imaging modalities.

In order to understand how the marker **10** works, it is instructive first to consider the different imaging mechanisms which may be employed in medical imaging.

Magnetic resonance imaging (MRI) operates by placing the imaging object in a high strength magnetic field. Currently, the field strength density typically varies from system to system between 0.2 and 3 T. In this strong magnetic field, the magnetic moments of hydrogen protons in the object become aligned with the magnetic field. By applying an electromagnetic signal having a resonant frequency to the object, the spins of those protons can be made to flip. When the electromagnetic signal is switched off, the protons flip back and emit an electromagnetic signal which can be received in receiver coils. Gradient magnets are employed to vary the magnetic field spatially, so as to generate detectable signals only from certain locations within the object and/or to make the resonant frequency differ at different locations

to enable spatial encoding of received electromagnetic signals. Hydrogen protons in different materials return to their equilibrium state at different relaxation rates, and this can also be used to differentiate between materials and construct images.

In this way, materials with high hydrogen proton densities, i.e. materials with high numbers of hydrogen protons which are free to flip their magnetic moment, are clearly and strongly visible in MR images.

Another imaging modality employs radiation such as x-rays. An object to be imaged is targeted with a collimated x-ray beam; typically the beam is cone-shaped, but other shapes could be employed. A detector positioned on the opposite side of the body detects the radiation after it has passed through the object. Some of the radiation will have been absorbed by the object, such that the data collected by the detector provides information on the location of the object in the form of a projection image. This technique is known in the art and termed herein as radiography. Multiple projection images can be combined to reconstruct a volume image of the object using computed tomography (CT) techniques. Note, positron emission tomography (PET) employs electromagnetic radiation in the form of gamma rays, but is not a radiographic technique.

The likelihood of an object absorbing x-rays of a given energy increases with increasing material density of the object, although the increase is not linear. High-density materials such as lead or tungsten absorb x-rays very readily, which leads to them being employed in collimators, radiation shields and the like. Low-density objects may not be visible in radiation-based images. The likelihood of absorption also depends on the energy of the radiation, with different mechanisms of interaction dominating at different energies. For example, in the case of lower energy x-rays (i.e. kV range), in addition to the effects of material density, x-ray absorption can be quite material sensitive due to the photoelectric effect. Different materials absorb kV x-rays differently (e.g. as seen in the clear imaging of bone in kV x-rays). However, at higher energy levels (i.e. MV range) the relative absorption depends mainly on the relative material density of the materials in the object. At MV energy levels, therefore, a high contrast image can be obtained by imaging materials with different material densities. The greater the difference in material density, the greater the contrast in the image.

The marker **10** according to embodiments of the present invention can be employed in imaging systems employing these and other techniques.

The marker **10** comprises a first marker component **12** which is solid and, in the illustrated embodiment, has a spherical shape. As will be explained in greater detail below, however, the first marker component **12** may take different shapes in different embodiments of the invention.

The first marker component **12** is non-magnetic, in that it has no significant effect on an external magnetic field (i.e. it is non-ferromagnetic). It is this feature which allows the marker **10** to be employed in magnetic resonance imaging (MRI) systems. Further, in some embodiments of the invention, the first marker component **12** is non-conductive, as conductive materials can cause distortion in MR images. In the context of the present invention, a component can be deemed non-conductive if the radio frequency field generated by an MRI system can penetrate (i.e. pass through) the component. The skin depth of the component material at such frequencies must therefore be substantially equal to or greater than the size of the component itself (the skin depth δ is given by

$$\delta = \sqrt{\frac{2\rho}{\omega\mu}},$$

where ρ is the resistivity, ω is the angular frequency and μ is the absolute magnetic permeability). For example, in a 1.5 T MRI the rf field frequency (the resonant frequency of hydrogen protons) will be at or around 64 MHz. Given this information, it is a simple exercise for the skilled person to select a suitable material to ensure that the skin depth is equal to or greater than the size of the component.

The first marker component **12** has a relatively high material density, so that it preferentially absorbs x-rays and appears in radiation-based images, i.e. radiographic images using x-rays. However, the first marker component **12** also has a relatively low hydrogen proton density, so that it appears only weakly in MR images. In some embodiments, the first marker component **12** has substantially zero hydrogen proton density so that it is not imaged in magnetic resonance imaging (MRI) systems.

One class of material which may be suitable for use in the first marker component **12** is ceramic materials, as they are non-magnetic and non-conductive. Certain ceramic materials also have a high material density, such as zirconium oxide (zirconia), which has a material density of 5.66 kgm^{-3}.

The marker **10** further comprises a second marker component **14**. The second marker component **14** is also non-magnetic (i.e. non-ferromagnetic), but has a relatively low material density (i.e. relative to that of the first marker component **12**) and a relatively high hydrogen proton density (again, relative to that of the first marker component **12**). In this way, the second marker component **14** is imaged more strongly than the first marker component **12** in magnetic resonance imaging (MRI) techniques, while the first marker component **12** is imaged more strongly than the second marker component **14** in radiographic techniques (i.e. in both MRI and radiographic images, a contrast is achieved between the two components).

In the illustrated embodiment, the second marker component **14** surrounds the first marker component **12**, but in other embodiments the second marker component **14** may only be in contact with the first marker component **12** on part of its surface such that, effectively, the two components have at least one common surface. In order that the second marker component **14** can easily conform to the surface of the first marker component **12**, the second marker component **14** may be liquid or a malleable solid. According to embodiments of the present invention, the second marker component may also be non-conductive, in that an rf field will penetrate the component as described above. For example, the second marker component **14** may comprise an oil, such as cod liver oil, or an oil-based solid. In alternative embodiments the second marker component **14** may comprise water or a water-based solution.

The marker **10** further comprises a housing **16** which substantially surrounds and supports the other components of the marker 1Q. In one embodiment the housing **16** supports the first marker component **12** at a fixed position within the housing **16**. The second marker component **14** substantially fills any voids in the housing **16** not filled by the first marker component **12**. The housing **16** may be manufactured from a plastic, such as poly(methyl methacrylate)—otherwise known as Perspex®—and may be transparent or opaque to visible optical light. The housing **16** is non-magnetic. It may also have a substantially zero hydro-

gen proton density and therefore be substantially invisible to magnetic resonance imaging (MRI) modalities.

In one embodiment, the housing **16** is not rotationally symmetric such that the second marker component **14**, which conforms to the shape of the housing **16**, is also not rotationally symmetric. In the illustrated embodiment the housing **16** is substantially cylindrical, but those skilled in the art will appreciate that alternative shapes could be employed without departing from the scope of the invention.

The first marker component **12** and/or the housing **16** may take a non rotationally symmetric shape such that their orientation can be determined more accurately when imaged. A spherical object can be easily imaged and measured, but cannot provide information on the orientation of the marker **10**. In certain situations that may not matter. However, a non-rotationally symmetric first marker component **12** and/or housing **16** can provide that information.

In further embodiments, the marker **10** may comprise multiple first marker components **12** within the housing **16**, each of which can be imaged positively using radiation-based techniques and negatively using MRI-based techniques.

FIGS. **2***a* and **2***b* are schematic illustrations of MRI-based and radiation-based images respectively of the marker **10** shown in FIG. **1**.

In FIG. **2***a* (MR imaging), the second marker component **14** is visible due to its high hydrogen proton density while the first marker component **12** is less visible (or even invisible) due to the relatively low hydrogen proton density. However, due to the common surface between the two components—shown in FIG. **2***a* as a dashed line—and the contrast between the two materials in the image, the first marker component **12** can nonetheless be visualized. That is, the spherical space within the second marker component **14** corresponds to the first marker component **12**, and therefore the first marker component **12** can be effectively imaged using magnetic resonance imaging (MRI) techniques.

In FIG. **2***b* (radiography), the first marker component **12** is directly visible as it has a higher material density that the second marker component **14**. The second marker component **14** also has a finite material density and therefore also appears in the image. However, due to the difference in material densities, the common surface of the two components (again shown by a dashed line) can be imaged. The centre of the first marker component **12** can therefore act as a common reference point in radiographic and MR images.

Note that the appearance of the first marker component **12** and the second marker component **14** in the radiographic image depends on a number of factors, including the energy of the radiation and the quantity of the radiation (i.e. as determined by the intensity of the beam and the exposure time). A small amount of radiation may result in the second marker component **14** effectively being invisible in the radiographic image. However, it is sufficient that only the first marker component **12** is visible, and that a boundary between the two components can be discerned.

In some embodiments it may desirable to decouple the size of the effective marker as imaged using radiographic techniques from the effective size of the marker **10** as imaged using MRI techniques. For example, a smaller first marker component **12** (i.e. the radiation absorbing component) increases the accuracy of calibration of a radiation based device, whilst use of a relatively large non-magnetic, low density material preserves the accuracy of calibration of a magnetic resonance imaging (MRI) device.

FIG. **3** shows a cross section of a marker **20** according to embodiments of the present invention. The marker **20** may be employed in an equivalent manner to that of the marker **10** shown in FIG. **1**.

The marker **20** comprises a first marker component **22** having equivalent material properties to the first marker component **12** described with reference to FIG. **1**, i.e. relatively high material density such that it appears in radiation-based images and relatively low hydrogen proton density so that it appears only weakly in MR images. However, in contrast to the first marker component **12** shown in FIG. **1**, the first marker component **22** of FIG. **3** has a relatively small volume such that its position can be ascertained more accurately when imaged using radiation based techniques.

The marker **20** further comprises a second marker component **24**. The second marker component **24** is equivalent to the second marker component **14** of the marker **10** described with reference to FIG. **1**. In other words, the second marker component **24** is non-magnetic (i.e. non-ferromagnetic), of relatively low material density and has a relatively high hydrogen proton density. Accordingly, the second marker component **24** is imaged more strongly than the first marker component **22** using magnetic resonance imaging (MRI) techniques, while the first marker component **22** is imaged more strongly than the second marker component **24** using radiographic techniques.

It will be appreciated that in the embodiment shown in FIG. **3**, no common boundary exists between the first marker component **22** and the second marker component **24**. However, in common with the embodiment described with respect to FIG. **1**, the coincident centre point of the first marker component **22** and the negative space defined by the second marker component **24** may be used as a common geometric reference point.

The first marker component **22** and the second marker component **24** are separated by an intermediate region **26**. In order to hold the first marker component **22** in position relative to the second marker component **24**, the intermediate region **26** may be fully or partially manufactured from a non-magnetic, non-metallic material having a relatively low density, such as poly(methyl methacrylate)—otherwise known as Perspex®. It may also have a substantially zero hydrogen proton density and therefore be substantially invisible to magnetic resonance imaging (MRI) modalities. The intermediate region **26** may be completely filled with such a material so as to encapsulate the first marker component **22**. Alternatively the intermediate region **26** may comprise a shell and one or more support members manufactured from plastic or similar material, arranged to hold the first marker component **22** in a concentric position relative to the shell such that the first marker component **22** and the void within the second marker component **24** have a common centre. In which case the remainder of the intermediate region **26** may be filled with air or any other material which is substantially invisible to magnetic resonance imaging (MRI) modalities.

The marker **20** further comprises a housing **28** equivalent to the housing **16** shown in FIG. **1** which substantially surrounds and supports the other components of the marker **20**. In one embodiment the housing **28** supports the intermediate region **26** at a fixed position within the housing **28**. The second marker component **24** substantially fills any voids in the housing **28** not filled by the first marker component **22** or the intermediate region **26**. Like the intermediate region **26**, the housing **28** may be manufactured from a plastic, such as Perspex® and may be transparent or opaque to visible optical light. It may also have a substan-

tially zero hydrogen proton density and therefore be substantially invisible to magnetic resonance imaging (MRI) modalities.

In further embodiments, the marker **20** may comprise multiple first marker components **22** and multiple corresponding intermediate regions **26** within the housing **28**. Each of the first marker components **22** may be imaged positively using radiation-based techniques, while the voids defined by the first marker components **22** and the intermediate regions **26** may be imaged negatively using magnetic resonance imaging (MRI)-based techniques.

FIGS. **4***a* and **4***b* are schematic illustrations of magnetic resonance imagine (MRI)-based and radiation-based images respectively of the marker **20** shown in FIG. **3**.

In FIG. **4***a* (magnetic resonance imaging (MRI)), the second marker component **24** is visible due to its high hydrogen proton density while the first marker component **22** and the intermediate region **26** are less visible (or even invisible) due to their relatively low hydrogen proton density. However, the border—shown as a dashed line—between the magnetic resonance imaging (MRI)-imageable second marker component **24** and the intermediate region **26** can be visualized due to their relative hydrogen proton densities.

In FIG. **4***b* (radiography), the first marker component **22** is directly visible as it has a high material density. The second marker component **24** also has a finite material density and therefore also appears in the image. However, due to its relatively low material density, this component **24** appears faintly. Equally, the intermediate region **26** has a relatively low material density and as such shows up faintly relative to the high density first marker component **22** in the image. Due to the difference in material densities of the first marker component **22** and the intermediate region **26**, the common surface between these two components can be imaged.

As with the marker **10** shown in FIG. **1**, the appearance of the first marker component **22** and the second marker component **24** and the intermediate region **26** in the radiographic image depends on a number of factors, including the energy of the radiation and the quantity of the radiation (i.e. as determined by the intensity of the beam and the exposure time). A small amount of radiation may result in the second marker component **24** and the intermediate region **26** effectively being invisible in the radiographic image. However, it is sufficient that only the first marker component **22** is visible, and that a boundary between the intermediate region **26** and the first component **22** can be discerned.

The utility of the marker **10** and the marker **20** will now be apparent to those skilled in the art. The same surface can be imaged using magnetic resonance imaging (MRI) and radiographic techniques, and moreover the centre of the first marker component **12**, **22** and the centre of the void in the second marker component **14**, **24** is the same, allowing the marker **10** and, the marker **20** to be employed in imaging systems using either or both modalities.

It will be apparent to those skilled in the art that in each of the embodiments described above, the first marker component **12**, **22** and the second marker component **14**, **24** may be swapped with each other without substantially affecting the ability of the marker **10** and the marker **20** to be imaged in radiographic and magnetic resonance imaging (MRI) modalities. For example, the marker may comprise a first (solid) marker component with a cut out for the second marker component.

In further embodiments, the first marker component **12**, **22** may have a lower material density than the second marker component **14**, **24**. As long as there is a difference between the two marker components in hydrogen proton density and material density, a contrast is achieved that allows the marker components to be imaged. It will however be appreciated that for radiation imaging, a relatively small marker component is preferable and for magnetic resonance imaging (MRI), a relatively large marker component is desirable.

As described above, phantoms are known devices which are scanned or imaged to evaluate and tune the performance of various medical imaging devices. In one embodiment, either of the marker **10** and the marker **20** themselves can be employed as a phantom. That is, the dimensions of the marker **10** and of the first marker component **12** may be made sufficiently large that an image of the marker **10** on its own provides sufficient accuracy to enable the imaging system to be calibrated. For example, if the first marker component **12** has a largest dimension in the order of 100 mm, the marker **10** may be placed in the imaging system on its own as part of the calibration process. Equally, if the first marker component **22** of the marker **20** has a largest dimension in the order of 100 mm, for example, the marker **20** may be placed in the imaging system on its own as part of the calibration process. Alternatively, a marker **10** and a marker **20** as described above and comprising multiple first marker components may be used on its own as a phantom.

However, sourcing and producing such a large device may be impractical due to issues of cost and efficiency. In other embodiments of the invention, either of the marker **10** and the marker **20** may be produced on a smaller scale such that the first marker components **12**, **22** have a largest dimension in the order of 10 mm. In this way, conventional phantoms can be adapted to include a plurality of such markers arranged in one or more patterns. FIGS. **5***a* and **5***b* show examples of such phantoms.

FIG. **5***a* shows a phantom **50**. The phantom **50** has a housing **52** which may be manufactured from a non-magnetic, non-conductive material such as plastic. In the illustrated embodiment the housing **52** is cylindrical but in practice any shape may be employed. The housing **52** has a number of attaching points (not illustrated), to which the markers **10** shown in FIG. **1** and/or the markers **20** shown in FIG. **3** are attached. Any means of attaching the markers **10** to the housing **52** can be used. For example, slots or openings may be provided in the housing **52**, into which the markers **10** can be inserted. In this example, the markers **10** are arranged in two circles, one at each end of the cylindrical housing **52**.

FIG. **5***b* shows a further example of a phantom **60** according to embodiments of the invention. In this example, the markers **10** are arranged in a helical pattern around the housing **52**.

In either case, the pattern of markers **10** allows the phantom's location and orientation to be precisely measured.

Whilst the phantom **50** shown in FIG. **5***a* comprises markers **10** of the type shown in FIG. **1** only, it will be appreciated that the housing **52** may additionally or alternatively include markers **20** of the type shown in FIG. **3**. The choice of which marker to use may depend on the particular device being calibrated or the accuracy of calibration required, amongst other factors.

It will be apparent from the description above that markers and phantoms according to embodiments of the present invention can be employed in imaging systems using a variety of imaging modalities, such as radiography and magnetic resonance. The markers and phantoms also have

particular utility within MRI-Linac systems, which combine both magnetic resonance imaging (MRI and radiotherapy within the same system. Such an MR-Linac system **100** is shown schematically in FIG. **6**.

The MRI-Linac system **100** comprises a gantry **102**, which is able to rotate about an axis I. A radiation head **104** is mounted to the gantry **102**, and adapted to generate a beam of radiation **106** directed substantially inwards towards the rotation axis I. A source of radiation (such as a linear accelerator, or a radioisotope) may be provided to generate the radiation which emanates from the radiation head **106**. In order to have a therapeutic effect, the energy of the radiation beam **106** will typically be in the order of megaelectronvolts. A patient support **110** is provided on or near the rotation axis I, on which a patient or an object to be imaged can be placed.

The shape and direction of the radiation beam **106** can be adapted by the use of collimators such as a multi-leaf collimator (not illustrated), to conform to a particular desired profile. For example, the shape of the radiation beam **106** may be adapted to conform to the profile of a target structure within a patient on the patient support **110**. As the gantry **102** rotates, the radiation beam **106** is directed towards the target structure from multiple directions and dose builds up in the target structure while being generally reduced in the surrounding areas.

A radiation detector **108** is mounted on the gantry **102** at a position substantially opposite the radiation head **104**, such that the radiation beam **106** impacts the radiation detector **108** after passing through an object to be imaged on the patient support **110**. Such detectors are often called portal imagers as they generate a projection image of the object along the axis of the radiation beam **106**. The radiation detector **108** is coupled to processing circuitry **112** which uses the detection data to produce an image. Thus, although the MRI-Linac system **100** is primarily used for therapeutic purposes and generates radiation beam **106** at an energy suitable for therapy, the radiation can nonetheless be used to generate images (albeit at lower contrast than the less energetic radiation conventionally used for imaging).

The MR-Linac system **100** further comprises a magnetic resonance imaging apparatus. Those skilled in the art will appreciate that such an apparatus comprises a large number of components, including various magnetic coils **114** for generating specific magnetic field strengths at specific locations and an RF system for transmitting and receiving electromagnetic waves. Only the magnetic coils **114** are illustrated here for clarity.

The magnetic coils **114** are positioned with their longitudinal axes aligned with the rotational axis I of the gantry **102**. In one embodiment, the magnetic coils **114** are displaced from each other along the direction of the axis I such that a gap is created. The radiation beam **106** can be directed through this gap such that the magnetic coils **114** do not interfere with the radiation beam **106**. The magnetic coils **114** are coupled to the processing circuitry **112** such that an image can be produced of an object on the patient support **110**.

An object which is placed on the patient support **110** can therefore be imaged by the MRI system and treated by the radiotherapy system while in the same position. Further, the radiotherapy system can be used to generate a portal image of the object using the radiation detector **108**. The markers **10**, **20** and phantoms **50**, **60** described above can be used to calibrate the MRI-Linac system **100** such that imaging data collected by the MRI system can be used to inform and control the radiotherapy system.

FIG. **7** is a flowchart describing a method of calibrating the MRI-Linac system **100** described above.

In step **200**, a phantom according to embodiments of the invention is placed on the patient support **110**, in the path of the radiation beam **106** and at a position suitable for imaging by the MRI system. The phantom may be a single marker **10**, **20** as shown in FIG. **1** or FIG. **3**, or a plurality of such markers as shown in FIGS. **5***a* and **5***b*.

In step **202**, the MRI system is used to generate an image of the phantom, and particularly used to generate an image showing the locations of the one or more second marker components. In this way, the first marker component can also be imaged because of the common boundary between the two component types.

In step **204**, the locations of the one or more first marker components are determined from the MRI image.

In step **206**, a radiographic image is generated of the phantom using the radiation beam **106** and the radiation detector **108** while in the same position. In this image, the one or more first marker components show more clearly due to their higher material density.

In step **208**, the locations of the one or more first marker components are determined from the radiographic image.

In step **210**, the knowledge of the first marker component locations in both images allows the coordinate systems of the magnetic resonance imaging (MRI) modality to be co-registered with the coordinate system of the radiographic modality. In particular, measurements using the MRI system can be used to instruct the radiotherapeutic system. For example, the positions of the collimating elements may be adapted on the basis of magnetic resonance imaging (MRI) data in order to track a moving target.

Embodiments of the present invention therefore provide markers, phantoms, and associated methods of calibration which are suitable for use in a wide variety of medical imaging systems.

Those skilled in the art will appreciate that various amendments and alterations can be made to the embodiments described above without departing from the scope of the invention as defined in the claims appended hereto.

The invention claimed is:

1. A marker for use in calibration of a medical imaging system, comprising:

a first component having a first hydrogen proton density and a first mass density, the first component being configured to absorb x-rays in a radiation-based imaging modality;

a second component having a second hydrogen proton density greater than the first hydrogen proton density, the second component able to be imaged in a magnetic resonance imaging modality, the second component further having a second mass density lower than the first mass density such that the second component is imaged less strongly than the first component in the radiation-based imaging modality; and

a common intermediate region made of a material which is not able to be imaged using the magnetic resonance imaging modality, wherein:

a surface of the first component and a surface of the second component abut the common intermediate region;

the first component, the second component, and the common intermediate region are non-magnetic; and

the second component comprises a void, the first component being positioned concentrically within the void.

2. The marker according to claim 1, wherein the common intermediate region has a third hydrogen proton density different than the second hydrogen proton density, and a third mass density different than the first mass density.

3. The marker according to claim 1, wherein the first component and the second component are such that a contrast is formed between the first component and the second component in the radiation-based imaging modality, and an opposite contrast is formed between the first component and the second component in the magnetic resonance imaging modality.

4. The marker according to claim 1, wherein the first component comprises a ceramic material.

5. The marker according to claim 1, wherein the first component has a substantially zero hydrogen proton density.

6. The marker according to claim 1, wherein the second component is a liquid.

7. The marker according to claim 6, wherein the first component is at least partially submerged within the second component.

8. The marker according to claim 1, wherein the first component comprises a spherical object.

9. The marker according to claim 1, wherein the first component comprises a rotationally asymmetric object.

10. The marker according to claim 1, further comprising a housing in which the first component and the second component are arranged.

11. The marker according to claim 10, wherein the housing is rotationally asymmetric.

12. The marker according to claim 1, wherein the first hydrogen proton density is lower than the second hydrogen proton density, and wherein the first material density is greater than the second material density.

13. A phantom for use in one or more medical imaging systems, comprising:

one or more markers according to claim 1.

14. The phantom according to claim 13, wherein the one or more markers comprise a plurality of markers according to claim 1.

15. The phantom according to claim 14, wherein the phantom comprises a housing having a plurality of attaching points to which the plurality of markers can be attached.

16. A method of calibrating an imaging apparatus, the method comprising:

placing a phantom according to claim 13 in an imaging volume;

generating an image of the phantom with the imaging apparatus; and

determining locations of at least one of the first component and the second components in the image.

17. The method of claim 16, wherein the imaging apparatus is integrated with a radiotherapy apparatus, the radiotherapy apparatus comprising a source of radiation generating a radiation beam passing through a treatment volume and a radiation detector for detecting the radiation beam after it has passed through the treatment volume, and wherein the treatment volume is coincident with the imaging volume, the method further comprising:

generating a radiation beam passing through the treatment volume and forming a second image of the phantom with the radiation detector;

determining locations of at least one of the first component and the second component in the second image; and

co-registering coordinate systems of the radiotherapy apparatus and the imaging apparatus.

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